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GEOMORPHIC FEATURES AND SOIL FORMATION OF ARID LANDS IN NORTHEASTERN JORDAN

GEOMORPHOLOGISCHE MERKMALE UND BODENBILDUNG IN TROCKENGEBIETEN IM NORDOSTEN JORDANIENS

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Arid and semiarid lands occupy about one-third of the Earth's land surface. Interpretation of soil formation and geomorphic features of arid lands is needed to assess their soil ecological potentials, limitations, problems and management needs. The objective of this paper was to study the geomorphic features and soil formation of the arid lands in northeastern Jordan, to provide information that could be used by land managers in the study area and other arid land areas. Five representative soil pedons were excavated and described in the field. Soil samples from each horizon per pedon were taken to the laboratory for chemical and physical analyses. Geomorphic features of the area were also studied. Most of studied land surfaces are plains where eolian deflation has exposed loose gravels consisting predominantly of pebbles forming desert pavements. Desert pavements cover most of the land surface, excluding the mud playas, and are composed of basalt clasts.

The accumulation of calcium carbonate and gypsum within these soils create problems for their agricultural development. Accumulation of eolian fine-grained silt has resulted in the formation of a vesicular horizon. The climatic variations during the late quaternary and the late Holocene periods contributed to the development of the desert pavement and the vesicular horizons. Clay illuviation and argillic horizon development within these soils is assumed to be a relict feature from more humid climates during the Quaternary. Sustainable agricultural development of such arid lands may not be easy. In general, these soils have high erodibility, high runoff generation potential, high susceptibility to seal and crust formation, poor water-holding capacity, pedon hardening and structural instability.

Keywords: Desert pavement; Gypsum; Calcium carbonate; Playa; Land management

INTRODUCTION

Arid and semiarid lands occupy about one-third of the Earth's land surface. They are sources and sinks for atmospheric CO_2, sources and sinks of global dust, and substrate that support a high biodiversity of plants and animals. The arid and semiarid lands of

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Jordan, locally known as the Badia, are one of the major dry areas in the world (Allison, 1997). The Badia encompasses a wide and significant part of Jordan. It covers an area of approximately 72 600 km^2, which constitutes 81% of the total area (89 400 km^2) of Jordan (Figure 1).

The Jordanian Badia is a part of the 'Mediterranean Sahara' because it is less arid than Arabian or African Sahara and has a smaller diurnal temperature range with all the sparse precipitation concentrated in the winter months. It is classified as a semiarid to arid steppe environment and falls in the arid climate zone (Dutton *et al.*, 1998).

The greatest part of eastern Jordan is desert, exhibiting the land forms and other features associated with aridic environments. Land use in the Badia region is mainly applied for agriculture (rainfed or irrigated), animal husbandry, and mining. These areas have also been important grazing lands for the local population over the years (Juneidi and Abu-Zanat, 1993).

Limited understanding of the processes involved in the formation of these arid lands makes it very difficult to fully utilize their soils in a sustainable manner. This research is a part of continued soil and geomorphic research efforts to investigate and evaluate the processes of arid lands formation. The objective of our research, therefore, is to study the geomorphic features and soil formation of these soils to provide information that can be used by land managers in this area and in other areas with similar conditions.

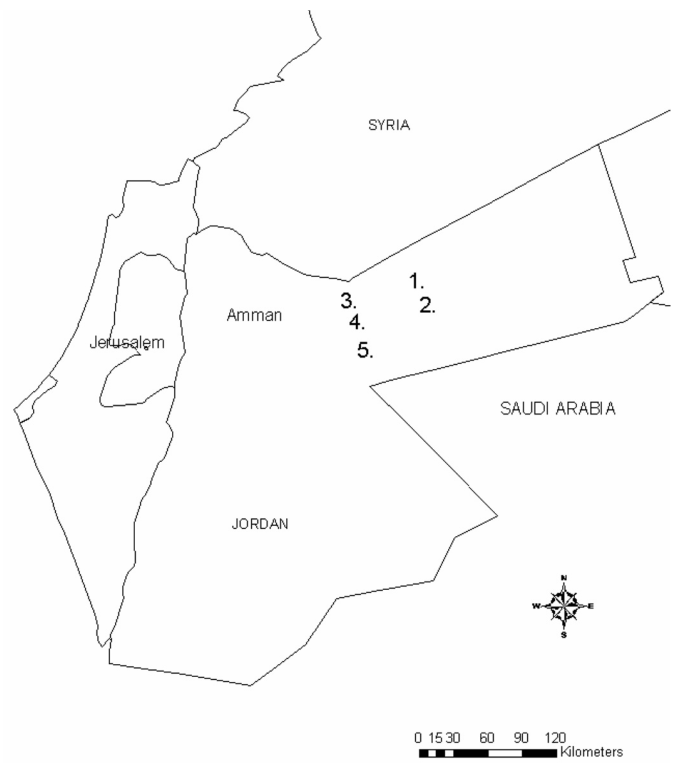

FIGURE 1 Map showing study site.

MATERIALS AND METHODS

The environmental conditions associated with the Badia arid environment, including low or sporadic moisture availability and high temperatures, are not ideal for plant growth. The vegetation of the Badia is sparse but enormously diverse. Despite that over 300 plant species have been identified, most of the Badia area is bare and lacking of vegetation cover (Cope and El-Eisawi, 1998; Dutton and Shahbaz, 1999). The grassland steppe; *Artemesia herba-alba, Poa sinaica* and *Carex pachystylis* form a distinctive, shallow rooting turf, with a root mat zone that provides protection against water and wind erosion. In overgrazed areas, these protective mats disappeared leaving soil more susceptible for erosion.

The Badia region falls in an arid climatic zone. Diurnal temperature ranges from mean minimum of 10°C to mean maximum of 24.5°C with mean daily temperature of 17.5°C. Precipitation is variable both spatially and temporally. Occasional heavy showers cause surface run-off and soil erosions that decrease the amount of water stored in the soil. A high evaporation demand caused by strong wind gusts and high temperatures exceed the amount of precipitation and therefore, decreases the water available for plant growth. Five soil pedons of different land use and different parent material types were chosen for the study. Those were excavated and sampled following Schoeneberger *et al*. (1998). Soil colour was defined using a Munsell Soil Colour Chart. Undisturbed soil samples were taken for particle size analysis.

The pedons were described according to Guthrie and Witty (1982). The bulk soil samples were air dried, crushed with a mortar and pestle, and sieved to remove coarse (> 2 mm) fragments. Particle size distribution was determined by the hydrometer method (Gee and Bauder, 1986). Organic matter was determined using the Walkley-Black method (Nelson and Sommers, 1982). Soil pH was measured on 1 : 1 soil : water suspensions (McLean, 1982). Calcium carbonate ($CaCO_3$) equivalent values were obtained using the acid neutralization method (Richards, 1954). Gypsum content values were obtained by precipitation with acetone method (Richards, 1954). Chemistry data can be found in Rawajfih *et al*. (2002). Descriptions of the five pedons and their classification according to the Soil Survey Staff (1998) and FAO (1998) systems are given in Table I.

RESULTS AND DISCUSSION

Geology and geomorphology

Most of study area land surfaces are plains where eolian deflation has exposed loose gravels consisting predominantly of pebbles but with occasional cobbles forming desert pavement, a sheetlike surface of rock fragments that remains after wind and water have removed the fine particles. Desert pavements cover most of the land surface excluding the mud playas (locally known as Marabs) and are composed of basalt clasts that range in size from cobble to granule near pedons 1 and 2; and chert clasts that range in size from cobble to granule in pedon 5. The predominate geomorphic features found near pedons 1, 2, 3, and 4 are desert pavements composed of basalt clasts, and outcrops of other more recent sediments with varying degrees of development. These desert pavements have not been well studied, however the data in this study suggest that these

TABLE I Classification (USDA; FAO) and Morphological characteristics of the studied sites*

Hor.	Depth, cm	Moist color	Structure	Consistence	Boundary	Remarks
			Pedon 1: (USDA: Typic Haplogypsid; FAO: Haplic Gypsisol)			
Ap	0–10	7.5YR 4/4	1 fgr	dh,mfr,wp	g	very common vesicles
By1	10–35	7.5YR 4/4	3 cabk	dh,mfr,wvp	d	common fine gypsum crystals
By2	35–90	7.5YR 4/4	3 cabk	dh,mfr,wvp	d	common fine gypsum crystals
Bty	90–140	5YR 3/4	3 cabk	dh,mfi,wvp	–	common fine gypsum crystals
			Pedon 2: (USDA: Calciargids; FAO: Haplic Calcisol)			
A1	0–3	7.5YR 5/6	1 mpl	dsh,mfr,wvp	a	vesicular horizon
A2	3–20	7.5YR 5/6	2 fgr	dsh,mfr,wvp	c	–
Bk	20–55	5YR 4/6	2 fsbk	dh,mfr,wvp	g	stage II carbonate.
Btk	55–140	5YR 3/4	2 msbk	dsh,mfr,wvp	-	fine gypsum crystals.
			Pedon 3: (USDA: Typic Calcigypsid; FAO: Yermic-Calcic Gypsisol)			
A1	0–4	7.5YR 4/6	1 mpl	dsh,mfr,wvp	a	vesicular horizon
A2	4–20	7.5YR 4/6	1 mgr	dh,mfr,wpo	d	no roots
By	20–60	7.5YR 5/4	3 msbk	deh,mefi,wpo	g	few gypsum crystals
Btky	60–100	7.5YR 4/4	3 msbk	deh,mefi,wpo	–	stage II CaCO3
			Pedon 4: (USDA: Typic Calcigypsid; FAO: Yermic-Calcic Gypsisol)			
A	0–4	7.5YR 4/6	2 mpl	dsh,mfr,wpo	a	fine basalt gravel
Btk	4–20	7.5YR 5/4	3 msbk	dvh,mfr,wp	gw	few faint clay skins.
Bky	20–75	10YR 5/6	3 msbk	dh,msfi,wp	–	stage II CaCO3
			Pedon 5: (USDA: Xeric Haplocalcid; FAO: Haplic Yermic Calcisol)			
Ap	0–8	7.5YR 5/6	2 mgr	dsh,mfr,wp	a	common fine and medium roots
Bt	8–20	7.5YR 4/6	3 cabk	dh,mfi,wvp	g	–
Bk1	20–40	7.5YR 4/6	3 mabk	dh,mfr,wp	c	stage II CaCO3
Bk2	40–120	7.5YR 4/4	3 msbk	dh,mfi,wp	–	manganese oxides coating

* The abbreviations are according to the Soil Survey Staff (1951).

desert pavements have formed through accretion of fine-grained eolian sediments similar to the findings of McFadden *et al*. (1987) and Anderson *et al*. (2002).

The soil parent material in the study area is diverse. Pedons 1, 2, 3 and 4 are located in areas of geologically recent (< 13 million years) basalt flows and the parent materials for these soils include alluvium and basalt fragments. Parent material for pedon 5 is limestone, marl, and chert alluvium.

Many of the surficial basalt clasts near pedons 1 and 2 show extensive eolian abrasion and are classic examples of ventifacts. In contrast, the chert clasts near pedon 5 do not show these features. The desert pavement plays an important role in the geomorphic, hydrologic, pedologic and ecosystem processes. Manganese, iron oxides, and hydroxides deposited on pebbles and cobbles resulted in dark black mineral staining (Desert varnish) on surfaces of the study area rocks.

Mud flats (Marabs)

These are sediment deposits which are parallel to the line of wadis and are known locally as Marab (also known as playa). Marabs (pedons 1 and 2) form where wadis exhibit relatively large discharges and are able to spread out across a wide area. There may be incision along the Marab, particularly towards the down-stream end where water becomes channel bounded.

Pedons 3 and 4 are located in a large low lying Marab (playa), forming an alluvial depression with highly gypsiferous soils. This area receives primarily sediments composed of limestone and chert from many of the major wadi systems draining from various directions. It forms a major part of the Azraq basin (Northeastern Badia). The drainage network is coarse and incised. In many areas, soil relief provides no eventual outlet to the sea, so that sedimentary deposits accumulate in basins (e.g., Azraq basin). In these basins, moisture evaporates leaving an accumulation of deposits such as anhydrite, gypsum, halite, calcite and other types of salts.

Surficial deposits in the study area cover most of the land surface. Coarse-grained granules, pebbles, cobbles and boulders of different lithologies are present above the modern day drainage levels in the area. The gravels are poorly sorted, angular to sub-angular, and sub-rounded. The geology varies greatly from basalt in pedons 1 and 2 to chert in pedons 3, 4 and 5.

Soil genesis

The formation, types, and properties of the studied soils are closely controlled by parent material, topography and climate. The major groups broadly follow geological variations, in particular the spatial distribution of desert pavements. While there are some characteristics that may be attributed to the present-day precipitation gradient, most of the differences seen in these pedons are the result of differences in their parent material and/or the different geomorphic processes experienced during the Quaternary. Different investigations suggested that climate in this zone had changed several times during the Quaternary.

Mineralogical studies (Irani, 1992) showed that the clay in this region has been subjected to extreme weathering conditions in previous wetter climates. The last of these changes was the present aridic climate (Rognon and Williams, 1977). The last episode of climatic changes is responsible for the development of unfavourable soil properties that accelerated the degradation of many plant species. Coupled with the effect of continuing drought incident, removal of plant cover was greatly enhanced (Taimeh, 1991). The climatic variations were as follows: pluvial period (40 000 – 20 000 years B.P.), dry interval (20 000 – 13 000 years B.P.), minor pluvial period (13 000 – 7000 years B.P.) and dry interval (7000 years B.P. – present).

Accumulation of eolian fine-grained silt has resulted in the formation of a vesicular horizon in pedons 2 and 3, and possibly in pedon 1. In addition, much of the silt, clay, carbonates, and soluble salts that have accumulated in the studied soils could be attributed to incorporation of eolian materials rather than to chemical weathering of soil parent materials.

Silt content increases towards the surface indicating eolian activity. However, clay content increased with depth indicating that enough illuviation of clay occurred so that argillic horizons were formed in some pedons (Table II). The presence of palygorskite and plagioclase at the surface indicates the weakness of chemical weathering and is attributed to eolian activities. High silt content leads to unfavourable soil properties (structure and crusting) and eventually unfavourable plant growth conditions.

The geomorphic position of the landscape greatly affects the soil characteristics. The main soil divisions are related to topographic and weathering differences. Pedons 1 and 2 have been strongly influenced by argillipedoturbation in the upper horizons. The presence of mafic rocks (basaltic) and the deposition of alluvium in Marabs favour the formation of smectites (Irani, 1992). The deep argillic horizons are considered to be inherited from past more humid climates. These soils exhibit cracks, but because of the

TABLE II Particle-size distribution (carbonate free) of the studied soils

Horizon	*Depth (cm)*	*Clay %*	*Silt %*	*Sand %*	*Texture*
Pedon 1					
Ap	0–10	46.4	33.8	19.8	Clay
Byl	10–35	51.3	32.2	16.5	Clay
By2	35–90	52.6	35.3	12.1	Clay
Bty	90–140	63.2	25.1	11.7	Clay
Pedon 2					
A1	0–3	47.9	31.0	21.1	Clay
A2	3–20	56.8	25.6	17.6	Clay
Bk	20–55	58.3	25.8	15.9	Clay
Btk	55–140	59.6	24.6	15.8	Clay
Pedon 3					
A1	0–4	48.2	39.0	12.8	Clay
A2	4–20	51.3	39.1	9.6	Clay
By	20–60	52.4	36.2	11.4	Clay
Btky	60–100	67.3	20.9	11.8	Clay
Pedon 4					
A	0–4	52.1	17.7	30.2	Clay
Btk	4–20	65.6	14.0	20.4	Clay
Bky	20–75	63.3	16.6	20.1	Clay
Pedon 5					
Ap	0–8	45.8	35.9	18.3	Clay
Bt	8–20	59.2	29.4	11.4	Clay
Bk1	20–40	61.3	28.6	10.1	Clay
Bk2	40–120	61.5	29.6	8.9	Clay

low shrink-swell potential and the size of cracks (less than 3 cm), these soils did not meet the requirements to be classified as Vertisols. The soil moisture regime for these two pedons is more properly xeric-aridic transitional rather than truly aridic since occasional floodwaters are carried into these basins. This moisture regime results in the accumulation of calcium carbonate and gypsum in these soils. The mean organic matter in the studied soils is less than 1.0% (Table III). The low soil organic matter content resulted in the presence of ochric epipedons in all of the studied soils. Therefore, a wide range of soils (Gypsiols, Calcisols) occur on older surfaces.

Calcium carbonate and gypsum accumulation

The horizons of carbonate accumulation are one of the most common diagnostic features in the study area (Table I). The accumulations vary from slight to great, characterized by carbonate filaments (stage I) to prominent stage II nodules, to stage III plugged horizons (Gile *et al.*, 1966). The calcic horizons in the study area are of pedogenic origin since their distribution is parallel to the land surface and their shape is mainly disseminated and segregated filaments and threads, nodules and concretions (Khresat, 2001). The depth of calcic horizons in these soils was highly related to the amount of precipitation and physiographic position. A common feature of these soils is the presence of a thick accumulation of secondary calcium carbonate (stage III and IV) on the basalt bedrock.

Unlike calcium carbonate, which is ubiquitous in desert areas, gypsum formation within soils needs a source of sulphate. The gypsic horizons occur in the middle and lower parts of the studied soils (Table I). The source of the sulphate and thus gypsum in

TABLE III Selected chemical properties of studied sites

Horizon	*Depth (cm)*	*$CaCO_3$ (%)*	*Gypsum %*	*pH (1:1)*	*OM (%)*
Pedon 1					
Ap	0–10	9.8	11.2	8.1	0.41
Byl	10–35	12.5	12.6	8.2	0.37
By2	35–90	13.0	14.5	7.9	0.21
Bty	90–140	12.0	16.8	7.9	0.33
Pedon 2					
A1	0–3	11.5	0.2	7.5	0.31
A2	3–20	11.2	0.1	7.4	0.27
Bk	20–55	16.3	0.2	7.2	0.28
Btk	55–140	17.2	0.5	7.4	0.24
Pedon 3					
A1	0–4	10.9	2.1	7.8	0.57
A2	4–20	11.1	5.6	8.0	0.43
By	20–60	11.3	17.3	7.7	0.41
Btky	60–100	17.5	15.1	7.8	0.35
Pedon 4					
A	0–4	12.6	1.3	8.8	0.51
Btk	4–20	18.7	8.7	8.5	0.45
Bky	20–75	20.3	12.4	8.0	0.42
Pedon 5					
Ap	0–8	14.1	0.0	8.6	0.98
Bt	8–20	15.7	0.1	8.5	0.34
Bk1	20–40	23.2	0.1	8.0	0.29
Bk2	40–120	24.8	0.2	7.9	0.20

these soils is presumed to be from eolian and/or fluvial deposition, or from dissolution of parent materials in place. For example, pedons 1, 3, and 4 likely receive gypsum-rich dust from local Marabs, including the large Azraq playa. The amount of gypsic dust received will impede the development of calcic horizons because of the common ion effect (Reheis, 1987; McFadden *et al.*, 1991; Buck and Van Hoesen, 2002).

Fluxes of different dust compositions with time, as well as the landscape position of the soil pedon can result in the wide range of soil types found in this study. Pedogenic gypsum in these soils occurs as small filaments (1 to 5 mm) or as snowballs approximately 0.5 to 2 mm in diameter as described by Buck and Van Hoesen (2002). In four of the studied pedons, gypsum occurs deeper within the pedon than calcium carbonate, reflecting its higher solubility. In pedon 1, gypsum dominates the pedon (instead of calcium carbonate) and is found in all of the horizons including the surface.

CONCLUSIONS

The climatic variations during the late quaternary and the late Holocene periods, which was characterized by being relatively dry period throughout the Badia region, contributed to the development of the desert pavement and the vesicular horizons.

The accumulation of calcium carbonate and gypsum within these soils create problems for their agricultural development, acting as cementing agents and can greatly limit the soil volume available for roots in addition to affecting water movement within the soil pedon. The presence of gypsum in some of the pedons may be somewhat useful in that it may help to lower the high pH of these soils. Recognition of gypsum in these desert soils is important because sulphate minerals can have a significant effect on a soil's physical and chemical characteristics.

The soils in this study show a wide range of features, but are dominated by carbonate, gypsum and clay illuviation and accumulation.

Clay illuviation and argillic horizon development within these soils is assumed to be a relict feature from presumably more humid climates during the Quaternary.

The organic matter content was generally low. Generally the organic matter content increased towards the surface. The low organic matter content of the studied soils contributed to land degradation. An increase of silt content lead to unfavourable soil properties (structure and crusting) and eventually unfavourable plant growth conditions. Consequently vegetative cover will be reduced which cause further degradation of soil.

The study area does not have sufficient vegetation to support grazing. These areas have been important grazing lands for the local population over the years. The heavy burden placed by livestock on these fragile soils left the soil surface bare and compacted during much of the fallow period and thus highly susceptible to wind and water erosion. Erosion by wind and water is considered the major cause of land degradation in the area.

The deficiency of water is a major characteristic of those soils. Their soil moisture is not sufficient enough to support plant growth. The natural vegetation is desert shrubs and short grasses.

Plant cover removal was greatly accelerated in the study area. Data on the extent of soil erosion are not compiled. However, field observations clearly indicated the severity of soil erosion in the study area.

The major restrictions to agricultural land use in this unit are a very low infiltration rate, low permeability, and high erodibility. These soils are moderately suitable for growing wheat or barley in good years of flooding. The studied soils have high erodibility, high runoff generation potential, and susceptibility to seal and crust formation, poor water-holding capacity, profile hardening, structural instability, and high surface temperatures in the summer months.

The high clay content and poor physical conditions of these soils make them very susceptible to erosion. Conservation measures that keep the surface covered and protect the soils from the impact of raindrops are recommended on those soils.

Those soils are suitable for crop production keeping in mind that annual cropping requires that land preparation is carried out annually, with the result that the land surface is bare for extended periods and thus exposed to the erosive effects of wind and water. All annual crops mature on residual moisture stored in the soil after the cessation of the winter rainfall. Available water holding capacity (AWC) is, therefore, very important; to ensure minimum acceptable yields during crop growth.

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